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THE ORIGIN OF RED BEDS

A STUDY OF THE CONDITIONS OF ORIGIN OF THE PERMO-CARBONIFEROUS AND TRIASSIC RED BEDS OF THE WESTERN UNITED STATES[1]

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PART I

PREFACE

SUMMARY DESCRIPTION OF THE FEATURES CONSIDERED
- List of Formations
- Colors of Gypsum and Limestone
- Color in Clastic Strata
- Distribution of Greenish Colors
- Nature of the Coloring Matter

IS THE FERRUGINOUS MATERIAL AN ORIGINAL CONSTITUENT OF THE SEDIMENTS, OR A LATER INTRODUCTION?
- Hypothesis of Introduction of Iron from Igneous Magmas
- Later Introduction of Iron by Meteoric Waters
- Deposition of Coloring Matter Contemporaneous with Sedimentation
- Microscopic Evidence
- Extent of Known Secondary Redistribution of Coloring Matter

IS THE FERRUGINOUS MATERIAL IN THE SAME FORM AS AT THE TIME OF SEDIMENTATION?
- Variations in Degree of Oxidation
- Origin of Mottling
- Cause of Gray and Green Bands in Red Beds: Barrell's Hypothesis
- Organic Matter the Controlling Influence in the Case of the Western Red Beds
- Variations in Hydration of Ferric Oxide

WAS THE COLORING MATTER A CHEMICAL OR A MECHANICAL SEDIMENT?

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[1] A revision of a thesis presented in partial fulfilment of the requirements for the degree of Master of Arts at the University of Wisconsin, in June, 1914.

PART II

CONDITIONS OF DEPOSITION OF RED CLASTIC SEDIMENTS: MODERN TYPES
    Red Clay of the Deep-Sea Bottom
    Stream Deposits Derived from Pre-existing Red Beds
    Arkosic Stream Deposits
    Stream Deposits Deriving Their Coloring Matter from Ferruginous Residual Soils
    Terrigenous Marine Clastics
    Deposits of Desert Lakes or Playas
    Red Dune Sands

EVIDENCE OF FEATURES OTHER THAN COLOR AS TO THE CONDITIONS UNDER WHICH THE RED BEDS WERE DEPOSITED
    Evidence of Conglomerates as to the Sites of Land-Masses
    Significance of Non-clastic Sediments
    The Clastics: Minor Structural Features
    The Clastics: Mineral Composition
    Evidence Supplied by Fossils
    Summary

RELATION OF OROGENIC HISTORY TO RED BEDS SEDIMENTATION

SUMMARY

PART I

PREFACE

Certain general facts concerning the origin of the western Red Beds have been known for some time and have become incorporated into current textbooks. There has been, however, much difference of opinion in the interpretation of some features of this remarkable group of sediments, especially as to the significance of the color itself. This paper is devoted to an investigation of the causes and history of the coloring matter, which, more than all other features put together, distinguishes the Red Beds from other sedimentary series.

The investigation on which this paper is based has been chiefly a study of the literature to which reference is made in the footnotes, together with all available published descriptions of the western Red Beds, and much miscellaneous literature dealing with related subjects. The writer's first-hand acquaintance with the Red Beds has been gained from two summers of field work in Wyoming and Idaho (under the direction of Eliot Blackwelder, of the United

States Geological Survey), and from laboratory study of thin sections. For valuable suggestions and criticism and for review of the manuscript the writer is indebted to Messrs. Eliot Blackwelder, A. N. Winchell, W. J. Mead, and F. T. Thwaites, of the University of Wisconsin; to Messrs. W. H. Emmons, C. R. Stauffer, F. F. Grout, C. J. Posey, and A. W. Johnston, of the University of Minnesota; and to Dr. R. D. Salisbury, of the University of Chicago.

SUMMARY DESCRIPTION OF THE FEATURES CONSIDERED

List of formations.—Clastic sedimentary strata of reddish color outcrop or constitute the uppermost part of the bedrock over about 4 per cent of the area of the United States and exist beneath a cover of younger sediments under an additional area probably twice as large. Much the greatest volume of such strata is included in the single group of rocks which forms the subject of the present study: namely, those Red Beds which outcrop in many areas from Kansas and Texas to Arizona and Montana (Fig. 1). The formations included in this group are related closely in age, ranging from Pennsylvanian to Triassic, or possibly Jurassic, and are probably for the most part physically continuous. They comprise the Cimarron series of Kansas and Oklahoma, and the Wichita, Clear Fork, Double Mountain, Greer, Quartermaster, and Dockum beds of Texas; the Wyoming, Fountain, and Maroon formations of central Colorado; the Cutler and Dolores of southwestern Colorado; the Aubrey, Shinarump, Vermilion Cliff, and Moencopie of the Colorado Plateau, with the Saliferous and Zuni of the Zuni Plateau in New Mexico; the Spearfish, Opeche, and Chugwater of Wyoming and southern Montana; and the Ankareh and Nugget of southeastern Idaho and northeastern Utah.

Similar Red Beds constitute a large part of the sediments of the Newark series (Triassic) of the Appalachian Piedmont region—typified by the Stockton and Brunswick formations of New Jersey.[1] They make up also, among others, much of the Catskill formation (Devonian) of eastern New York and Pennsylvania; the Medina and Clinton (Silurian) of New York; the Vernon shale (Silurian, a

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[1] See H. B. Kümmel, *Ann. Rept. of the State Geologist of New Jersey*, 1896.

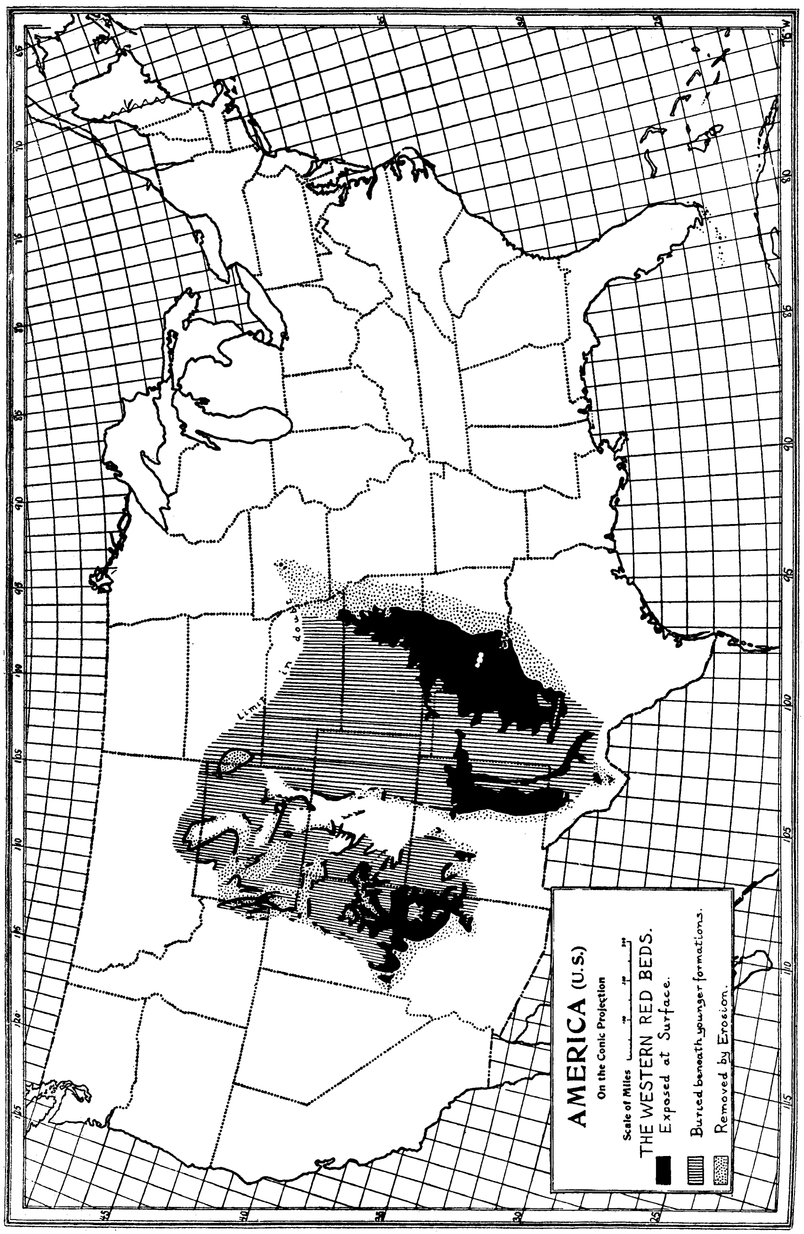

FIG. 1.—Map showing distribution of the western Red Beds

member of the Salina beds), the Bedford shale (Mississippian), and the Dunkard series (Permian) of Ohio; the Lake Superior sandstone (probably Algonkian) of northern Michigan, Wisconsin, and eastern Minnesota; and the Belt series (Algonkian) of Montana and British Columbia. Occasional reference will be made in this paper to these formations, and to Red Beds in other countries as well; but this discussion applies especially to the western group, with which the writer is most familiar.

Colors of gypsum and limestone.—The beds of gypsum occurring in many areas of Red Beds strata are described everywhere as remarkably pure and white, except where stained by a red coating washed down from overlying clastic sediments. The same is true of a majority of the limestones and dolomites occurring in the red series, most of which are gray or drab or bluish on fresh fracture. Even the famous Redwall limestone (2,500 feet thick) underlying the Aubrey Red Beds of the Grand Canyon section is gray on fresh fracture;[1] its surface color is due to concentration of iron oxide by weathering, to wash from above, or to both of these causes. Exceptions are found in limestone or dolomite bands in the lower Chugwater in Wyoming,[2] and in the Minnekahta limestone[3] of the Hartville quadrangle, which are characteristically purplish or rosy gray; and locally in certain limestones in northern Oklahoma, where they are in transition to sandstone.[4] These limestones are in most localities nearly or quite barren of fossils.

Color in clastic strata.—Another and perhaps a yet more significant fact is the variation of hue among the clastic strata. Interbedding of greenish, gray, or buff beds with red sediments is found in a majority of Red Beds sections; notably in the Saliferous of the Colorado and Zuni plateaus, in the Dockum group of Texas, and in the Red Beds of the San Juan region and of the Anthracite, Crested Butte, and Tenmile quadrangles of Colorado. Alternation of paler with darker and with brighter shades of red is remarked in almost every occurrence of Red Beds. In all these instances it is significant that the color boundaries tend to follow bedding planes, and usually accompany changes in coarseness of grain. Many of the color boundaries are distinct, even planes, but they may be rendered irregular by downward migration of coloring matter.

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[1] G. K. Gilbert, "Geology of Portions of Nevada, Utah, California, and Arizona," *U.S. Geog. Surveys W. of the 100th Meridian*, III (1875), 177–78.

[2] Eliot Blackwelder and C. W. Tomlinson, "Field Notes on Work in Western Wyoming, 1910 and 1911," unpublished; property of the United States Geological Survey.

[3] W. S. T. Smith, Hartville Folio (No. 91), *Geol. Atlas of the U.S., U.S. Geol. Survey*, 1903.

[4] J. W. Beede, "The Neva Limestone in Northern Oklahoma," *Okla. Geol. Survey Bull. No. 21*, 1914, p. 24.

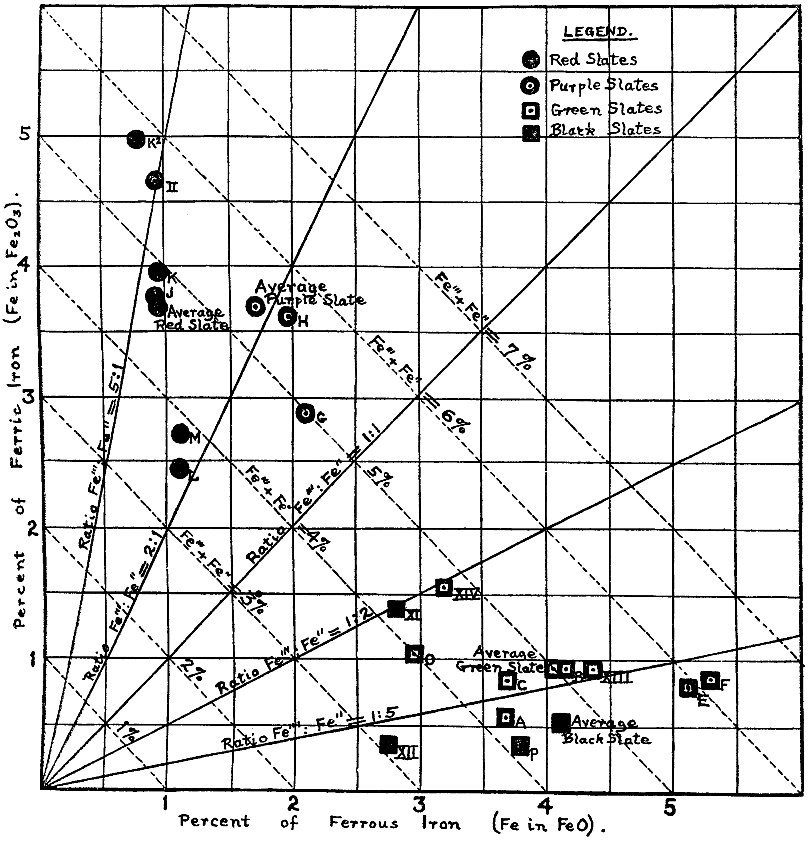

FIG. 2.—Diagram to illustrate the relation between color and the proportion of ferric to ferrous iron in ferruginous slates. Analyses (from Dale) are lettered to correspond with text.

Where alternations of light- and dark-red strata occur, the more deeply colored beds are in most cases of finer grain than the others. The occurrence of coarse-grained massive buff sandstones in a series of maroon or chocolate shales has been noted by many writers. This association holds true in many other Red Beds besides the group here under consideration. Thwaites[1] reports it as an almost unfailing relation in the Lake Superior sandstone series of northern Wisconsin, and Geikie[2] mentions its existence in the Triassic New Red Sandstone of Great Britain. The respective tints are understood to be uniform throughout the strata in which they are noted, and not to be merely the surface staining of the beds, which might have a very different origin.

Distribution of greenish colors.—Greenish tints occur in the Red Beds as a fairly even color through continuous beds interstratified more or less closely with red strata, in streaks and blotches in red strata themselves, and occasionally in strips following joint planes. The completely greenish strata, and likewise the mottled beds, include both shales and sandstones, and are described from many districts. Green spots in red strata are as a rule irregularly ellipsoidal in shape, somewhat flattened parallel to the bedding, and indefinite in outline. They may vary in diameter from a few millimeters to several inches.

Variations in color along the strike are as common and as much to be expected as similar variations in texture, cross-bedding, or any other stratigraphic feature. The Red Beds of the Southwest are noted for their inconstancy and frequency of change along the strike; those of Central Wyoming and the Black Hills are fairly continuous in lithologic characters for considerable distances. Where other features are variable, the color is variable also; and where other features are constant, color likewise is constant.

Nature of the coloring matter.—Available data as to the chemical composition of the green bands and spots and other variations in color in the western Red Beds are very meager; but many of the same phenomena occur in roofing slates, whose commercial value has been the cause of painstaking investigation of their occurrence and character. The close dependence of color upon chemical composition is brought out strikingly by the following analyses, which are at least sufficient to show that the differences in color in the Red Beds are caused by the same differences in chemical composition as those which cause corresponding differences in color in slates. The analyses are plotted graphically in the diagram (Fig. 2).

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[1] F. T. Thwaites, "Sandstones of the Wisconsin Coast of Lake Superior," *Bull. Wis. Geol. and Nat. Hist. Survey No. 25*, 1912, p. 31.

[2] Archibald Geikie, *Text-Book of Geology* (London: Macmillan, 1903), p. 1064.

The following analyses are taken from Dale:[1]

		Fe_2O_3	FeO	Net Fe	Ratio Fe‴: Fe″	Free Carbon
Red slates	J.........	5.36	1.20	4.69	4.04 :1.00	(No free carbon found in any of the red or purple slates)
	K.........	5.61	1.24	4.89	4.09	
	L.........	3.48	1.42	3.54	2.29	
	M.........	3.86	1.44	3.83	2.42	
	K²*.......	7.10	1.00	5.75	6.37	
	Average...	5.26	1.21	4.62	3.91 :1.00	
Purple slates	G.........	4.10	2.71	4.99	1.36 :1.00	
	H.........	5.16	2.54	5.59	1.84	
	II.........	6.63	1.20	5.58	5.00	
	Average...	5.30	2.15	5.38	2.22 :1.00	
Green slates	A.........	0.81	4.71	4.23	0.156:1.00	
	B.........	1.34	5.34	5.09	0.226	Trace
	C.........	1.23	4.73	4.54	0.234	Trace
	E.........	1.12	6.58	5.90	0.155	
	F.........	1.24	6.81	6.16	0.165	
	O.........	1.47	3.81	3.99	0.348	
	XIII......	1.33	5.64	5.31	0.213	Trace
	XIV......	2.24	4.07	4.73	0.496	
	Average...	1.35	5.21	4.99	0.232:1.00	
Black slates	P.........	0.52	4.87	4.15	0.095:1.00	0.46
	VII.......	....	9.03	7.02	0.000	1.79
	XI........	1.98	3.65	4.23	0.490	0.77
	XII.......	0.53	3.52	3.11	0.135	1.54
	Average...	0.75	5.27	4.63	0.129:1.00	1.14
Spotted slates	M*.......	3.86	1.44	3.83	2.42 :1.00	
	Q*........	1.79	1.19	2.18	1.34 :1.00	
	R*........	1.09	1.06	1.58	0.927:1.00	

* K² is same slate as K, but finer grained. M = red slate near green spot. Q = purple rim of spot. R = green part of spot.

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[1] T. N. Dale, "The Slate Belt of Eastern New York and Western Vermont," *Ann. Rept. U.S. Geol. Survey No. 19*, 1899, Part 3, pp. 232, 246–53, 257, 264; and "The Roofing Slates of the United States," *U.S. Geol. Survey Bull. No. 275*, 1905, pp. 34–36.

The following analyses are taken from W. J. Miller:[1]

VERNON FORMATION, CENTRAL NEW YORK

	Fe_2O_3	FeO	Net Fe	Ratio Fe‴ : Fe″
Red shale	2.25	0.75	2.16	2.72:1.00
Green spot in red shale	0.00	1.19	0.93	0.00:1.00

The following analyses were furnished by Eliot Blackwelder:[2]

CHUGWATER FORMATION, WIND RIVER VALLEY, WYOMING

	Fe_2O_3	FeO	Net Fe	Ratio Fe‴ : Fe″
Red sandstone	3.50	1.04	3.26	3.02:1.00
Greenish sandstone*	1.03	1.04	1.53	0.89:1.00

*The greenish sandstone of the Chugwater in this case is a strip of the ordinary red sandstone, leached along a joint crack.

The following analyses are taken from Richardson:[3]

SPEARFISH FORMATION, BLACK HILLS

	Fe_2O_3	FeO	Net Fe	Ratio Fe‴ : Fe″
Green shale	1.85	1.04	2.02	1.78:1.00
Red shale, adjacent to green	4.61	1.24	4.55	3.72:1.00
Red shale	3.64	0.65	3.05	5.04:1.00
Red shale	2.04	0.18	1.57	10.20:1.00

The black color in the slates is due, not directly to any peculiarity of the iron content, but to the presence of carbonaceous matter, which incidentally brings about the reduction of iron oxide to the ferrous form. Black shales are very rare in the western Red Beds, but highly carbonaceous and even coal-bearing strata occur in the Newark series of the Atlantic Piedmont. The typical Newark clastics are quite intensely red, many of them with a purplish tone, but the carbonaceous strata are always gray or black.

The color of the prevailing red strata in the Red Beds series is due to the presence of ferric oxide. The iron of the coloring matter is chiefly in the ferric state in light- and dark-red, buff, and yellowish strata. A gray or green color, on the contrary, signifies a low proportion of ferric oxide, and usually a preponderance of ferr*ous* over ferr*ic* compounds. The mineral composition of the coloring matter is difficult to determine accurately because of its fine division. A green color is "common with silicates in which ferrous iron is prominent,"[1] and silicates may be important where the ratio of ferrous to ferric iron is high.

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[1] W. J. Miller, "Origin of Color in the Vernon Shale," *Bull. N.Y. State Museum*, No. 140, in *63d Ann. Rept. N.Y. State Museum, 1909*, I, 150–56.

[2] U.S. Geol. Survey, Division of Chemistry, Analysis No. 2530.

[3] G. B. Richardson, "The Upper Red Beds of the Black Hills," *Jour. Geol.*, XI (1903), 365–93.

IS THE FERRUGINOUS MATERIAL AN ORIGINAL CONSTITUENT OF THE SEDIMENTS, OR A LATER INTRODUCTION?

Hypothesis of introduction of iron from igneous magmas.—If the ferruginous matter was an integral part of the original sediments, we have no more difficulty in explaining its presence than in accounting for any other common mineral constituent of sedimentary rocks. Its source was most probably in the same rocks which gave rise to other materials of the series, such as quartz, feldspar, and calcite, and the agencies of transportation were the same as those which were responsible for the entire series. If, however, we postulate that the iron has been introduced since the completion of sedimentation, after the series of Red Beds was otherwise complete, we shall find it very difficult to reconstruct in imagination any natural agency which might have brought about such a result, and we shall be puzzled to find an adequate source for this vast amount of iron.

There is one hypothesis of this kind which received credence and vigorous support in America for several decades of the nineteenth century, in explanation of the red stain in the Newark series of the Connecticut Valley.[2] The close association, in that series, of clastic red sediments with contemporaneous extrusive and intrusive basic igneous rocks of great thickness and extent made it a natural suggestion that the exceptional color of the sedimentary members was connected directly with igneous action. The absence of any strong evidence in support of this hypothesis, aside from that of association with igneous rocks, and the discovery of various lines of evidence (among those outlined below) in direct opposition to it, however, caused it to fall into disrepute. In the case of the western Red Beds there is not even the association with igneous rocks to suggest such an explanation. There are no contemporaneous igneous rocks in any part of the Red Beds group, and in the greater part of the area in which the group occurs there are no later igneous rocks known. In no case is there a relation comparable to that in the Connecticut Newark.

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[1] E. S. Dana, *A Text-Book of Mineralogy* (New York: John Wiley & Sons, 1909), p. 472.

[2] See J. D. Dana, *Manual of Geology*, ed. 1880, p. 764; and also his review of Russell's bulletin on the "Subaerial Decay of Rocks" (*U.S. Geol. Survey Bull. No. 52*, 1889), in *Am. Jour. Sci.*, 3d Ser., XXXIX (1890), 319.

Where the effect of later intrusions upon Red Beds has been observed carefully, that effect is not to heighten, but to destroy, the red color. This action has been noted in the Tenmile district[1] and in the Anthracite-Crested Butte district,[2] Colorado.

Later introduction of iron by meteoric waters.—There is no apparent reason why the Red Beds should have been favored by post-sedimentational iron-bearing solutions while other clastic series in the same region, both older and younger, were not stained. It might be expected that the coloring matter would be most abundant in the most pervious strata, especially along the lower surface of such strata, where they are in contact with less pervious rocks. It is quite true that color boundaries in the series follow bedding planes very closely; but, unfortunately for the hypothesis of later introduction, the more highly ferruginous strata of the Red Beds are as a rule, and with few exceptions, the more impervious. As noted above (pp. 158–59), in a series of alternating sandstones and shales it is almost invariably the shales which are deeper in color.

Ferric hydrates are not being introduced into the Red Beds strata along the present joint planes. The analyses of Chugwater sandstone given on p. 161 (see also footnote) show a marked leaching of iron along a joint. Nor is iron commonly concentrated along joints in paler sediments underlying the Red Beds.

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[1] S. F. Emmons, Tenmile District Special Folio (No. 48), *Geol. Atlas of the U.S., U.S. Geol. Survey*, 1896.

[2] G. H. Eldridge, "Description of the Sedimentary Formations," Anthracite-Crested Butte Folio (No. 9), *Geol. Atlas of the U.S., U.S. Geol. Survey*, 1894.

Deposition of coloring matter contemporaneous with sedimentation.—If the ferruginous material which furnishes the color was concentrated in the sediments chiefly at the time of their deposition, this association of high color with fine sediment is explained readily, as follows:

In the weathering of igneous rocks, ferruginous material is separated out chiefly by the chemical decomposition of iron-bearing silicate minerals, and is therefore at the time of separation in a very fine state of division. At the same time ferrous salts of iron usually are altered to ferric oxide or hydrate. During surface transportation and sorting it is segregated in whole or in part, by reason of this fine division (if it persists) and in spite of its high specific gravity, along with other finely divided materials constituting muds and "clays."

This does not apply to iron occurring in the parent rock in the form of magnetite or other very stable minerals, which in most cases are concentrated with the coarser products of mechanical disintegration, such as sands and sandy shales. Ferruginous materials firmly cemented to sand grains during weathering may also be transported and deposited with the sand. Iron taken into solution will have yet a different history.

In the weathering of sedimentary rocks, the behavior of their ferruginous content is dependent upon the behavior of that material in a former sedimentary cycle, and thus ultimately upon the conditions already outlined for the weathering of the igneous rocks. Ferric oxide, the form in which iron occurs most abundantly in sediments, is, because of those conditions, usually finely divided, and in a second cycle of transportation and deposition will be concentrated again chiefly with the muds. In so far as assortment is imperfect, the ferruginous material may be deposited with any type of sediment.

Because of the usual absence of any commercial value in the series, there is an unfortunate dearth of analyses of Red Beds shales and sandstones. The fact of the concentration of ferruginous matter in the fine-grained sediments is well illustrated, however, by composite analyses of shales and sandstones from all sources. The following figures from Clarke[1] are to the point:

	Percentage Fe_2O_3	Percentage FeO	Total
Average of 78 shales (mean of two composites) ..	4.03	2.46	6.49
Composite analysis of 253 sandstones...........	1.08	0.30	1.38

See also analyses K and K^2, on p. 160, *supra.*

Microscopic evidence.—Russell[2] has presented evidence to show that the red coloring matter in sandstones of the Newark series in Virginia occurs as a coating on the sand grains, and that it existed in that form even before the transportation of the sand from the residual soils from which it was derived. Since much of his argument would apply equally well to the red sandstones of western Red Beds, it is worth investigation in this connection. In a few thin sections of Newark sediments from Virginia which have been available for study by the writer, it is shown clearly that ferruginous matter exists there, both in the form described above and as a later interstitial filling between grains. Many of the sand grains, both of quartz and of feldspar, are well rounded. Most of them are surrounded by a thin coat of hematitic material, whose outer surface is smooth and even, but whose inner border may show slight irregularities penetrating into the body of the grain. This red film may not be entirely continuous around the grain; and this fact, together with the smoothness of its outer surface, suggests, as Russell maintained, that the coating was acquired by the sand grain before its final deposition, and that the coating suffered wear during transportation, without being completely removed.

In a number of instances it was found that part of the cementation of the rock had been accomplished by enlargement of the original grains of quartz and feldspar in optical continuity, outside of the red coating; and that outside of the enlargements there existed other bodies of hematitic matter, irregularly scattered through the interstitial spaces. This material may have filtered in during the process of cementation; or it may have been present at the time of sedimentation and have been thrust out of the way by the growing crystals during enlargement. Occasional specks of red-stained material are found within the area of the enlargements and distinct from the inner coating of the original grains; and where the enlargement is missing, the interstitial hematitic matter may be difficult to distinguish from that of the primary coating. The stained areas probably do not represent pure ferric oxide, but ferric oxide in such ratio to silica or clayey material as to render the mixture nearly opaque and quite uniformly red or reddish brown; for chemical analyses of the same rocks show the percentage of ferric oxide in the rock to be much lower than the percentage of red-stained area in the sections.

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[1] F. W. Clarke, "The Data of Geochemistry," 2d ed., *U.S. Geol. Survey Bull. No. 491*, 1911, chaps. iii, v, vi.

[2] I. C. Russell, "Subaerial Decay of Rocks," *U.S. Geol. Survey Bull. No. 52*, 1889.

A similar microscopic investigation has been made by Richardson[1] in his study of the Spearfish formation of the Black Hills. He says: "Amorphous red pigment is prominent in the slides. It irregularly coats and spots the minerals, and . . . . constitutes the chief interstitial substance."[2] He also presents an analysis to show that the ferric oxide of the pigment is essentially anhydrous.

Thin sections of Red Beds from all parts of the West are not available at present, and it has not been practicable, therefore, to make a thoroughgoing microscopic study of the group. Richardson's description suggests a relation of pigment to cementation similar to that found in the Newark sandstones: a twofold relation, indicating that part of the pigment was transported and deposited as a coating on sand-grains, and that the remainder constitutes an important part of the cementing material of the rock and is coeval with the rest of that material.

But what was the time of cementation? Was this process completed before the exposure of the Red Beds series to erosion, or is it still going on, or did it cease at some intermediate time? In so far as this question affects the iron content of the Red Beds we really have answered it already; for if any considerable part of the iron had been introduced as a cement later than the time of sedimentation it would not be found most abundantly in the strata which afford the least ready passage to water, as is actually the case. The cementing material of the Red Beds, in so far at least as it is ferruginous—and the remainder of it has little or no bearing upon the point in question—was therefore for the most part present in those beds at the time they were deposited as sediments.

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[1] *Op. cit.*

[2] *Ibid.*, p. 379.

Extent of known secondary redistribution of coloring matter.—Although the evidence is convincing that the ferruginous matter in the Red Beds was an integral part of the original sediment, and that it was deposited originally in the series in practically its present distribution and arrangement, it is equally certain that there have been some later modifications of that primary distribution. A large majority of all variations of color within the Red Beds are limited by bedding planes; but there are numerous minor variations in color due to the migration of coloring matter along the lines of movement of ground-water.[1] Reducing solutions locally extract ferruginous matter along joints, or cause a general downward movement of iron. In the western Red Beds, as in Barrell's section of the Catskill formation in Schuylkill County, Pennsylvania,[2] the lower boundaries of many deeply stained bands are drawn less sharply than the upper. All of these are very minor features, however, in the distribution of the coloring matter of the series as a whole. The analyses (p. 161) furnished by Blackwelder illustrate the effect of leaching along a joint; the color changes from red to greenish, the net iron content is reduced from 3.26 per cent to 1.53 per cent, and the ratio of ferric to ferrous iron drops from 3.02:1.00 to 0.89:1.00.

IS THE FERRUGINOUS MATERIAL IN THE SAME FORM AS AT THE TIME OF SEDIMENTATION?

Variations in degree of oxidation.—Is the color due to recent oxidation in weathering? It has sometimes been asserted that the color of the Red Beds is a superficial matter, due to the weathering of originally dull-colored sediments. In support of this idea drill records have been quoted, showing that beyond a certain depth below the surface the rocks are no longer red. S. F. Emmons states, respecting the Maroon formation of the Tenmile district, Colorado,[1] that "in depth, as shown in underground workings, the red color generally gives way to a greenish gray." In another paragraph of the same folio, Emmons states that igneous or hot-water alteration destroys the red color. Inasmuch as the ores of this district are related intimately to igneous and hot-water action, it is natural to suppose that mine workings would be the most likely of all places in which to find such effects. The relation here described is probably a local and abnormal phenomenon.

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[1] Cf. Richardson, *op. cit.*, p. 376.

[2] See Joseph Barrell, "The Upper Devonian Delta of the Appalachian Geosyncline," *Am. Jour. Sci.*, 4th Ser., XXXVI (1913), 437 ff.

In his description of the sedimentary rocks of the Anthracite and Crested Butte quadrangles, where the general situation is similar to that in the near-by Tenmile district, Eldridge[2] states that "the upper division [of the Maroon conglomerate] is of a peculiar red or chocolate color, except in regions of local metamorphism" of the kind mentioned also by Emmons.

Drilling explorations in the oil regions of Oklahoma and Texas recently have given us some additional information on the behavior of the color with depth. Gould[3] tells of a well some 3,300 feet deep in southeastern Oklahoma, in which "the last of the typical Red Beds was encountered" at a depth greater than 2,000 feet. The underlying strata were dull-colored sediments like those outcropping along the eastern (lower) margin of the Red Beds. Nowhere does he mention any change in color due to depth.

A well sunk 3,095 feet at Ashland, Wisconsin, passed through typical red sandstones of the Lake Superior group all the way, without any suggestion of a change in color with depth.[4]

It is to be remembered that most of the western Red Beds series are not colored uniformly throughout, but include many lighter-colored strata; and that many of the Red Beds successions include gray and green members. Any drill cutting through such a series would find, of course, changes in color with depth, but they would not be progressive, and they would have no causal connection with depth whatsoever.

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[1] *Op. cit.* [2] *Op. cit.*

[3] C. N. Gould, "Petroleum in the Red Beds," *Economic Geology*, VIII (1913), 768-80.

[4] Data from F. T. Thwaites, *op. cit.*

This variegation itself constitutes one of the most unanswerable arguments against weathering in the present cycle as the cause of the red color. The distribution of gray and green beds among the red does not appear to have any definite relation to coarseness of grain, as in the case of intensity of the red color, nor to any other single stratigraphic feature; and it certainly bears no constant relation to the topographic surface.

Origin of mottling.—The green spots present in some otherwise red strata have been explained, on the hypothesis that the red color is due to recent oxidation in weathering, as remnants of the original color of the beds; but, as will be shown presently, it is much better in accordance with fact to explain them as spots in originally red sediments, deoxidized by the agency of some particle of organic matter which was present in the original sediment.

Dale[1] discusses the origin of the green spots in red and purple slates in part as follows:

> The difference in color from the green to purple to red is manifestly due to the differences in the amount of hematite. [See analyses, p. 160.] The green fossil impressions in purple slate may throw some light on the origin of these spots. In this case the effect of organic matter, whether the carbonaceous matter of the lining of an annelid boring or from a marine alga, has been to diminish the quantity of Fe_2O_3 in the slate. The increase of the carbonates may be directly connected with the production of CO_2 by decaying organisms and the consequent decrease of the Fe_2O_3. In view of all these facts and indications, the spots may be safely regarded as probably produced by chemical changes consequent upon the decay of organisms.

The same conclusion is reached by Miller with respect to green spots in the red Vernon shale (Silurian, central New York). Miller[2] finds dark organic centers in many of the spots, and attributes the color of green shales associated with the red strata to more abundant dissemination of organic matter.

It is probable that a very small quantity of organic matter may reduce or prevent the oxidation of a considerable amount of iron. The ferruginous matter necessary to stain a sediment is so small in amount that the quantity of organic matter necessary to accomplish the reduction of a patch less than an inch in diameter, like most of the green spots in Red Beds, is so small that it could easily be effaced or removed. A tiny fragment of vegetable fiber or the remains of a few minute organisms of any kind probably would suffice.

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[1] T. N. Dale, The Slate Belt of Eastern New York and Western Vermont, *Ann. Rept. U.S. Geol. Survey No. 19*, 1899, Part 3.

[2] *Op. cit.*

Cause of gray and green bands in red beds: Barrell's hypothesis.—Barrell[1] states that in the Catskill formation of eastern Pennsylvania gray and green colors are typical of sandstones, and red colors of shales. He therefore suggests a causal relation between coarseness of grain and condition of the iron content, as follows:

> These relations show that there was a tendency toward deoxidation during the formation of the beds of sand, of oxidation during the deposition of the Catskill muds. Where the clay and iron oxide were sparing in quantity, the deoxidation was effective. The conditions which accompanied the deposition of clay and iron oxide also permitted oxidation to dominate over deoxidation.[2]
>
> The lack of oxidation of the iron in the sandstones, in spite of its lesser quantity, suggests that more abundant ground-waters in the sands may have kept out the air and permitted the organic matter to accomplish its effects, or perhaps that here the ratio of organic matter was in excess of the ferric oxide.[3]
>
> A few rare carbonaceous streaks have been observed in the Catskill and the plant impressions are in places found in deoxidized shales. Coaly and pyritiferous plant fossils are also preserved in some of the olive sandstones.[4]

No actual remnants of organic matter are reported to have been found in *red* strata, though markings interpreted by Barrell as rootlet marks are noted by him in certain horizons of red shales.

That physical conditions of deposition alone should have favored oxidation in the finer-grained sediments and retarded it in the coarser seems highly improbable. Where meteoric water moves most freely, there the most oxygen is carried in solution. The more rapid the circulation of ground-waters, the more effective are those waters as oxidizing agents, instead of vice versa, as suggested by Barrell.

For the lesser quantity of iron in the sandstones we already have offered an explanatory hypothesis (p. 164). The smaller the amount of ferric oxide present in a sediment, the smaller, of course, is the amount of organic matter necessary to bring about its reduction—or the reduction of a sufficient part of it to mask the color of the remainder. If organic matter were distributed equally among all the sediments of the series, it would cause gray and green colors in the sands rather than in the muds, by reason of the mechancial concentration of ferric oxide in the latter. The ratio of ferruginous materials to organic matter seems to be the dominating factor in determining the colors of ferruginous beds. Barrell's second suggestion in the foregoing quotation, dealing with this point, deserves more careful investigation.

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[1] *Op. cit.*

[2] *Ibid.*, p. 458.

[3] *Ibid.*, p. 469.

[4] *Ibid.*

Much of the organic matter carried as sediment in surface waters tends to be concentrated with the muds, for reasons analogous to those already suggested in the case of ferruginous material (i.e., fine division); but the proportion so concentrated is probably smaller in the case of organic matter than in that of ferruginous material, because of the indiscriminate distribution of driftwood, the growth of vegetation in most regions of clastic deposition, and other similar factors. In any of these cases organic matter in large quantities may enter into the composition of sands and muds alike, and thus bring about a higher ratio of organic to ferruginous matter in the sands than in the muds.

These controlling factors are so complex that no constant relation between coarseness of grain and distribution of organic matter is to be expected. It is evident from the quotations on p. 170 that definite organic remains in the section there under consideration are confined chiefly to gray and green strata; and it is also evident that such strata include both shales and sandstones. An examination of the detailed section[1] of the Catskill formation published by Barrell in this paper reveals a somewhat less uniform relation between coarseness of grain and color of beds than one would understand to be the case from reading the text or the labels on the graphic columnar section.[2] Of the 3,864 feet of beds definitely described as of one or the other type, 2,179 feet (56.4 per cent) bear out Barrell's generalization that gray and green colors are typical of sandstones and red colors of shales, 901 feet (23.3 per cent) are noncommittal, and 754 feet (20.3 per cent) are in opposition to the rule. This variability is in better accord with the complexity of the factors controlling the distribution of organic matter in sediments than a more constant relation would be; and suggests that even here the distribution of organic matter may be a controlling influence in determining the colors of the individual strata.

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[1] Barrell, *op. cit.*, pp. 451–56.

[2] *Ibid.*, p. 457.

Dawson,[1] in discussing the Triassic (?) Red Beds of Nova Scotia, says of the gray sandstones and shales interstratified with them, that "where thick, they always contain either fossil plants, bituminous matter or thin seams of coal, or all of these. The following sentence from Geikie,[2] relative to the Old Red Standsone of the British Isles, is also interesting in this connection: "It may be observed also that where gray shales occur intercalated among the red sandstones and conglomerates they are often full of plant remains, and may contain also ichthyolites and other fossils which are usually absent from the coarser red sediments."

Organic matter the controlling influence in the case of the western Red Beds.—Nowhere in the literature on the western Red Beds is there suggested such a definite and relatively constant association of green and gray colors with sandstones, and of red with shales, as that which Barrell sees in the Catskill formation, and as that which is described as occurring in the Siwalik formation of India.[3] In the foregoing quotation from Geikie, the opposite relation is implied in the Old Red Sandstone series of Great Britain. In the Red Beds of the western United States variegation is perhaps more common in shales than in sandstones, though it occurs to a marked extent in both.[4] The distribution of gray and green colors in the Red Beds coincides very closely with the distribution of organic remains in the same series, in so far as such remains are present; and this close association, together with the chemical probabilities of the case, suggest that organic remains now obliterated explain at least the greater part of the remaining gray and green areas and strata. The decolorization of these sediments may, therefore, have been complete before their burial under later strata. The occurrence of traces of organic matter in red strata may be explained by an unusually high content of ferric oxide in those strata, or by later reoxidation of iron at one time in the ferrous state. The fact that much the greater part of the occurrences of colors characteristic of ferrous compounds are in distinct beds with definite boundaries, indistinguishable in most other characteristics from other beds which are not so colored, is good evidence that this distribution of ferrous and ferric compounds, or of the substances responsible for these compounds, was accomplished for the most part at the time of sedimentation. It is well to remember that the gray and greenish strata are very subordinate in the Red Beds of the western United States.

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[1] J. W. Dawson, "On the Colouring Matter of Red Sandstones and of Greyish and White Beds Associated with Them," *Quar. Jour. Geol. Soc. London*, V (1848), 25–30. Quotation from p. 26.

[2] Geikie, *op. cit.*, p. 1003.

[3] Medlicott and Blanford, *A Manual of the Geology of India*, II (1879), 524–26. Quoted by Barrell, *op. cit.*, pp. 463–64.

[4] Cf. Permian of the Pecos Valley and of the Zuni and Colorado plateaus; and the Jura-Trias Painted Desert sandstone of the latter plateau.

The general conclusion to be drawn from the preceding discussion is that there has been in the western Red Beds no extensive change of ferrous to ferric iron, or vice versa, since the time of sedimentation; and also that the original distribution of these compounds in the series was influenced most largely by the distribution of organic matter.

Variations in hydration of ferric oxide.—That various degrees of hydration exist in the ferric oxide of the Red Beds today is clear from the variety of red, brown, and yellow hues which appear in some members of the group. The major part of the ferric oxide in the Red Beds is no doubt but poorly hydrated.[1] The bright- and deep-red and red-brown colors (which are most common in the western series) may be attributed to hematite (anhydrous Fe_2O_3) or to turgite ($2Fe_2O_3 \cdot H_2O$). The lighter browns, yellow-browns, and yellow tints are referable to göthite ($Fe_2O_3 \cdot H_2O$) or limonite ($2Fe_2O_3 \cdot 3H_2O$), or possibly in some cases even to xanthosiderite ($Fe_2O_3 \cdot 2H_2O$).

The freer passage of water through the sandstones as compared with the shales makes the constituents of the former, after consolidation, more susceptible of hydration than those of the latter. It is entirely probable that in some cases at least this factor of porosity heightens the contrast in color between coarse and fine sediments; but it apparently has not affected the greater part of the Red Beds, in which the ferric oxide is relatively anhydrous. Van

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[1] Cf. Richardson's investigation, discussed on p. 166.

Bemmelen has shown that chemically prepared ferric hydrate, after being partially dehydrated, if placed in a medium saturated with water vapor, at ordinary temperature, takes up again part of the lost water.[1] Brescius went so far as to say that "when nearly dry, ferric hydrate has almost as great a tendency to take up water as oil of vitriol itself."[2] This does not appear to be true, however, of hematite found in nature. Once *completely* dehydrated, ferric oxide becomes a stable compound.

It remains to inquire into the means by which dehydration of the more hydrous compounds might have been accomplished to produce the low hydrates, in case these were not originally in the same condition. The first agent of dehydration which presents itself is that of heat. Elsden makes the following statement:

> The influence of temperature and moisture upon the iron hydrates is well known. In the case of laterite in India, the yellow xanthosiderite soon weathers to reddish-brown turgite, owing to dehydration. In the hot and arid regions of South California the soils are dark red in colour, the iron being in the form of hematite instead of the hydrous forms, göthite or limonite. Dehydration also takes place in the hot regions of the Southern Appalachians, where the air is comparatively humid. It is only the deeper portions of the soil which retain the iron in a hydrated form.[3]

In all of the above mentioned cases, the source of the heat which produces the reaction in question is the sun's rays. Its action in the soils is limited to a superficial stratum rarely more than 15 feet in maximum depth.[4] Obviously, the direct influence of insolation cannot be responsible for any extensive dehydration in the Red Beds, whose characteristic colors are known to extend to depths of more than 2,000 feet.[5]

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[1] J. M. Van Bemmelen, "Sur le colloide de l'oxyde ferrique," *Recueil des travaux chimiques des Pays-Bas et de la Belgique*, VII (1888), 112.

[2] E. Brescius, "Researches on Ferric hydrate," abstract in *Jour. Chem. Soc. London*, XXIV (1871), 497.

[3] J. V. Elsden, *Principles of Chemical Geology* (London: Whittaker & Co., 1910), p. 97.

[4] W. O. Crosby, "On the Contrast in Color of the Soils of High and Low Latitudes," *Amer. Geologist*, VIII (1891), 74; E. A. Smith, *Geol. Survey of Alabama, Rept. for the Years 1881 and 1882*, p. 186.

[5] See p. 168.

Another source of heat which might be suggested is that of igneous intrusions. The absence of igneous rocks in the greater part of the western Red Beds, including the regions where drilling has shown the colors to be unchanged at depth, proves that this has not been a factor of widespread importance. Heat due to regional metamorphism or to structural deformation of any sort must likewise be discredited here, as the Red Beds are substantially flat-lying over vast areas, and are nowhere intensely deformed or metamorphosed, except locally in the immediate neighborhood of igneous bodies.[1] That compression due to the weight of overlying sediments may have created sufficient heat for the accomplishment of extensive dehydration must be recognized as a possibility, although in many areas where the Red Beds occur the requisite overlying sediments are not known ever to have existed, and the uppermost members of the series in these localities are as brilliantly red as any below them. Furthermore, pressure creates heat only by the performance of mechanical work, and microscopic study of the Red Beds reveals no evidence of internal deformation.

Crosby[2] concludes that the process of dehydration of ferric oxide is largely a spontaneous one, which goes on independently of any outside influence whatsoever, though aided by high temperatures. He states as evidence in support of this hypothesis that the red sedimentary formations and the red iron ores of the world occur in the older systems chiefly, while in the younger systems ferruginous formations and ores are commonly yellow. There are, however, many exceptions to this rule, such as the buff Cambrian sandstones of the Mississippi Valley, the modern red residual iron ores of Cuba, and the dark-red hematitic bog ores in Sweden and elsewhere; and furthermore, the dehydration of the pre-Cambrian red sandstones and argillites may be attributed in some cases partly to regional metamorphism, which has not affected the younger beds.

Richardson[3] has given much weight to this "essentially spontaneous" process. He states that "the dehydration of ferric hydrates tends to go on under ordinary conditions without any unusual cause."[4] "This has been repeatedly demonstrated by experiment."[5] But none of the experimenters to whom Richardson refers[1] appears to have considered the observed dehydration as truly "spontaneous"; and certainly they have shown the process to be closely dependent upon external conditions. The chemically precipitated colloidal ferric hydrates possess, when first formed, a higher content of water than any of the forms known to occur as minerals. According to Van Bemmelen,[2] on standing in a dry medium at ordinary temperatures these colloids gradually approach the composition $2Fe_2O_3 \cdot H_2O$, beyond which the percentage of combined water is not reduced without the application of much higher temperatures. Under water, or in air of moderate humidity, they have not been shown to lose water beyond the composition $Fe_2O_3 \cdot 2H_2O$ except at temperatures above 50° C.,[3] and heating at 50–60° C. for 2,000 hours failed to bring about dehydration beyond the composition $2Fe_2O_3 \cdot H_2O$.[4] Temperatures as high as these cannot be assumed to have existed, except locally, in the Red Beds sediments since burial. The so-called spontaneous dehydration observed in the laboratory is probably subject to the terms of Van Bemmelen's conclusion: "The red-brown substance, which has been considered to be a hydrate, is a colloid . . . . which has no stable composition; it maintains an equilibrium with the tension of the water vapour in the surrounding medium."[5] Since burial, the great mass of the Red Beds sediments, except in the most arid districts of the West, have been saturated with ground-water, a condition decidedly unfavorable to dehydration at the temperatures there existing.

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[1] See p. 168.

[2] *Op. cit.*

[3] *Op. cit.*, p. 392.

[4] *Ibid.*

[5] *Ibid.*

Yet another agent of dehydration is mentioned by Elsden:

> The presence of any substance in solution which lowers the vapour tension of water will lower the inversion temperature of gypsum. . . . . Even solid

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[1] J. M. Van Bemmelen, "Sur le colloide de l'oxyde ferrique," *Recueil des travaux chimiques des Pays-Bas et de la Belgique*, VII (1888),106–14; Edward Davies, "Action of Heat on Ferric Hydrate in Presence of Water," *Jour. Chem. Soc. London*, XIX (1866), 69–72; G. C. Wittstein, "Über das Verhalten des Eisenoxyhydrates unter Wasser," *Vierteljahreschrift für praktische Pharmacie*, I. Band (1852), 275–76.

[2] *Op. cit.*, pp. 110–11.

[3] T. Carnelly and James Walker, "The Dehydration of Metallic Hydroxides by Heat," *Jour. Chem. Soc. London*, LIII (1888), 89; D. Tommasi, "Ferric Hydrates," abstract in *Jour. Chem. Soc. London*, XLIV (1883), 24.

[4] Davies, *op. cit.*, p. 70.

[5] Van Bemmelen, *op. cit.*, p. 114. Translated from the French.

> gypsum . . . . can be changed into anhydrite by a concentrated solution of sodium chloride. . . . . These facts are of interest as pointing to the possibility of dehydration of minerals in rocks, in contact with salt solutions, at a temperature considerably below their normal inversion point.[1]
>
> . . . . The occurrence of red ferruginous sandstone in conjunction with layers containing brown hydrated ferric oxide is less readily explained [than the superficial dehydration of soils, mentioned in the quotation on p. 174, *supra*], but the dehydration of certain beds may have been effected by contact with salt solutions, as in the case of gypsum already referred to above.[2]

Dehydration by contact with salt solutions presumably would affect the more porous beds first; whereas in the western Red Beds, as already described,[3] it is generally in the more porous beds that the lighter colors occur, and the shales are in general of deeper hue than the sandstones. Just how far the action of salt solutions may have been effective, both during and since sedimentation, in accomplishing dehydration in the neighborhood of such saline deposits as occur in the Red Beds, it would be difficult to say; but for the group as a whole it appears that this agency cannot have been of general importance.

In summation, it may be said that while widespread dehydration of iron oxide in the Red Beds since sedimentation cannot, at present, be proved not to have taken place, the greater weight of evidence now at hand is opposed to it; that the opposite process, hydration, may well have been active in the more pervious beds of the series; and that, therefore, the probabilities are quite as much in favor of a lower degree as of a higher degree of hydration, on the average, in the Red Beds at the time of sedimentation than at present.

WAS THE COLORING MATTER A CHEMICAL OR A MECHANICAL SEDIMENT?

Having determined as nearly as the available evidence permits the condition of the coloring matter of the Red Beds at the time of their deposition, we may proceed to inquire as to the geographic conditions which gave rise to sediments so colored. The first question to be answered in this connection is: Was the ferruginous matter deposited as a mechanical or as a chemical sediment?

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[1] Elsden, *op. cit.*, pp. 85–86. See also H. Stremme, "Zur Kenntnis der wasserhaltigen und wasserfreien Eisenoxydbildungen in den Sedimentgesteinen," *Zeit. für prakt. Geol.*, January, 1910, pp. 18–23.

[2] Elsden, *op. cit.*, p. 97. P. 158–59.

The general absence of coloring matter from the non-clastic members,[1] which are in very large part inorganic chemical precipitates, indicates quite clearly that the conditions favoring free chemical deposition of calcium and magnesium carbonate or of calcium sulphate were not those under which the coloring matter was usually deposited. The close limitation of ferruginous material to the clastic sediments proves that the conditions under which clastic sedimentation took place favored the deposition of iron oxide also, and strongly suggests that that material itself was carried and deposited as a mechanical sediment, for the most part at least. In this connection it is of interest to note that Dawson[2] drew a similar conclusion as early as 1848 with reference to the contrast in color between the clastic and non-clastic strata of the Red Beds of Nova Scotia.

The condition of the ferric oxide in the Red Beds sediments, as revealed by the microscope, is one of very fine division. Since fine division is to be expected from the mode of origin of the ferric oxide in soils,[3] this cannot be taken as evidence that it is a chemical precipitate, in place, in the rocks. If it were the latter, definite orientation of crystals of hematite with respect to peripheries of grains might be looked for. I never have seen this phenomenon in thin sections of Red Beds sediments. The microscopic evidence is therefore rather noncommittal as regards the present question.

The processes of weathering leave much the greater part of the iron content of all types of rock as a residue in the soil, subject to mechanical transportation. All of the other common chemical constituents of rock, with the probable exception of alumina, are leached from the soil more rapidly than ferric iron. The scarcity of iron in any form in the surface waters of the continents, abundantly shown by the analyses of lake and river water published by Clarke,[4] and its even greater scarcity in the ocean,[5] testify to the fact that chemical deposition of salts of iron is only exceptionally an important process in earth metamorphism. Glauconite, the most common of such deposits at the present time, is of such peculiar nature as to be readily recognized where it occurs in older sediments: it certainly is not involved to any appreciable extent in the origin of the Red Beds. Bog iron ore, the only other common type of ferruginous chemical precipitate at present, is connected intimately, in origin, with abundance of vegetation and with peculiar and limited topographic conditions; and although deposits of this type are scattered over many parts of the world, none of them is comparable in extent or in thickness to even the smallest of the Red Beds areas. Furthermore, no deposits similar in textural character to bog ores are known in the western Red Beds.

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[1] See p. 157. [2] *Op. cit.* [3] See p. 164.

[4] F. W. Clarke, "The Data of Geochemistry," 2d ed., *Bull. U.S. Geol. Survey No. 491*, 1911, chap. iii.

[5] *Ibid.*, chap. iv.

In view of the facts above stated, it seems a safe conclusion that the coloring matter of the Red Beds was transported and deposited almost if not quite wholly as a mechanical sediment; and, therefore, without danger of serious error, we may limit investigations of possible conditions of origin of this coloring matter to those which would produce it as a mechanical sediment purely. This applies to the gray and green members of the Red Beds series as well as to those in which the iron is present chiefly as ferric oxide; for if the ferrous iron in the former be explained as the result of the action of organic matter deposited in those strata,[1] the ferruginous matter may have been in the ferric form during transportation, quite as well as in any other.

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[1] See pp. 170–72.

[*To be continued*]